2016 Conference on Systems Engineering Research

Uses of Exergy in Systems Engineering

Andrew Gilbert[a]*, Dr. Bryan Mesmer[a], Dr. Michael D. Watson[b]

[a]University of Alabama in Huntsville, Huntsville, AL 35899
[b]NASA Marshall Space Flight Center, Huntsville, AL 35812

Abstract

The topic of exergy has sparked much interest in recent years as a system level attribute to aid in the systems engineering design process. Exergy is defined as the useful work available to a system. It is an overall system level metric which integrates across subsystems, disciplines, and the couplings between each. Exergy based analysis methods provide advantages over traditional engineering methods in the search for elegant designs. This paper provides an overview of exergy, exergy based methods, and examples of the uses of exergy in a variety of fields. A brief discussion of the use of exergy in rocket design and optimization is also included. Furthermore a vision for multiple areas of exergy research is presented.

© 2016 The Authors.

Keywords: Exergy; System Metrics; Exergy Analysis; Exergy Efficiency; Thermoeconomics; Entropy;

Nomenclature

e	specific exergy, J/kg
h	enthalpy, J/kg
V	velocity, m/s
g	acceleration due to gravity, m/s^2
z	altitude, m
R	universal gas constant, J/kg-K
T	temperature, K
c	specific exergy content, J/kg
s	specific entropy, J/kg-K

* Corresponding author. *E-mail address:* atg0006@uah.edu

mp	mass of propellant, kg
mveh	total mass of vehicle, kg
1,2	state of system process

1. Introduction

Exergy is defined as the useful work available to a system in reference to its environment, or dead state[1]. Sciubba defines exergy as "the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment by means of processes in which the system interacts only with this environment.[2]" It is important to note here that useful work is any reversible work done to or by a system; however, all real processes are irreversible by nature. Therefore, exergy analysis is a synthesis of the first and second laws of thermodynamics[3], seen in Figure 1.
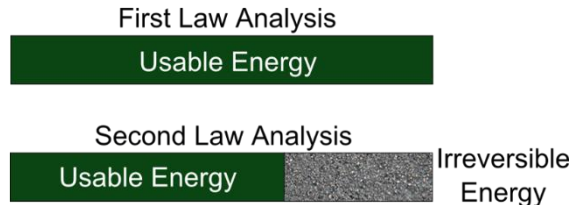
First Law Analysis
Usable Energy

Second Law Analysis
Usable Energy Irreversible Energy

Figure 1: First and Second Laws of Thermo

For a system that proceeds from state 1 to state 2, there exists a state function of the system's specific exergy (J/kg) variation. This state function is given in equation 1[2].

$$e_1 - e_2 = h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2) + \left(\Delta g_{1,0} - \Delta g_{2,0} + RT_0 \ln \left[\left(\frac{c_1}{c_{1,0}} \right) \right] - T_0 (s_1 - s_2) \right) \quad (1)$$

The left hand side of equation 1 represents the change in exergy of the system. The right hand side represents different forms of energy use. The first term on the right side of equation 1 is specific enthalpy, the second term is specific kinetic energy, the third term is specific potential energy, the fourth term is specific chemical energy, and the final term is the irreversible entropy generation, or exergy destroyed. Because exergy is taken with reference to environment, the exergy content of a system can change even if the state of the system does not[2].

Exergy based analyses can also be expressed in terms of overall system efficiencies. Three definitions of exergy efficiency are provided by Sciubba[2]: the "Second Law" efficiency in equation 2, the degree of reversibility in equation 3, and the coefficient of exergetic destruction in equation 4.

$$\varepsilon = \frac{useful\ exergy\ output}{used\ exergy\ output} \quad (2)$$

$$\psi = \frac{exergy\ of\ "products"}{\sum exergy\ inputs} \quad (3)$$

$$\xi = \frac{annihilated\ exergy}{total\ exergy\ input} \quad (4)$$

As can be seen in the above equations, exergy represents a holistic characteristic of a system that can be related to many different systems and subsystems. Because of this broad definition the systems engineering community has become interested in exergy to help describe large-scale complex engineered system and provide guidance in the design process of such systems. This paper addresses multiple areas of research that the authors envision exergy

being a key component of. Work in these areas will identify if exergy is a useful system attribute as well as form a foundation for the use of exergy in the design and systems engineering process.

2. Motivation

Large-scale complex systems consist of a large number of subsystems, each potentially consisting of a large number of components. The traditional practice of engineering these systems is flawed. These flaws have been the cause of an estimated $200 million[4] dollars per day lost due to project cost and schedule overruns. One reason for these flaws is that the current way the requirements-based approach is conducted does not communicate holistic preferences about the system to all system designers, from the stakeholder down to the lowest design engineers. A meaningful, holistic approach or modification of traditional approaches is needed in order to provide a clear preference to the designers to enable systems that are consistent with the preferences of the stakeholder.

In large-scale complex systems the many subsystems and components exist in distinct and different disciplines, such as mechanical and electrical. Each discipline has its own set of traditional engineering methods which may not be applicable to the others. For example, a finite element analysis (FEA) used in mechanical engineering would have limited applicability in electrical engineering. Therefore, a need exists for an overall system metric that is able to integrate subsystems across disciplines and domains. Because most, if not all, subsystems depend on energy in some form, exergy provides this overall system metric[5]. Such a metric enables disciplines that were previously optimizing their own objectives to now focus on an objective that can be shared across disciplines, leading to more consistent decisions being made throughout the design process if that objective is the preference of the stakeholder. Figure 2 shows just a few of the domains that share exergy as a common metric.

3. Exergy and Design

An overarching problem in systems engineering is the determination of what is a good design. Without a holistic preference stated and quantified by the stakeholder the engineers are left questioning what the best design is. Griffin[6] has identified four attributes that he believes define what he describes as elegant designs. Four attributes of design elegance are ascribed:

- the system design must be effective
- the system design must be robust
- the system design must be efficient
- the system design must minimize undesired consequences

A system that is effective is a system that produces the expected outputs for a range of expected inputs. As systems grow more complex, the number of subsystems grows along with the interactions between these subsystems. Traditional analysis approaches, such as analyzing the stress of a beam, are unable to cross the
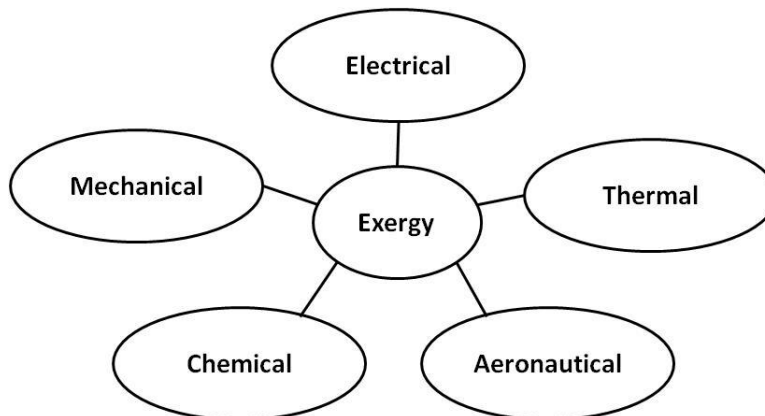
Figure 2: Domains Sharing Exergy

multitude of disciplines found across subsystems. In addition, the subsystems themselves can exist in a multitude of states, which further complicates the task of traditional engineering analysis. Exergy based analysis provides a state function that encompasses multiple domains and disciplines by using energy as a common currency. Exergy analysis also takes irreversibilities into account, something which most traditional engineering methods do not. A better assessment of realistic system performance can be gained via the evaluation of these irreversibilities. By encompassing all the domains, couplings, and irreversibilities present in the state of a system, exergy provides a vital overall system metric which is useful in design search.

Multidisciplinary Design Optimization (MDO)[7]–[12] is a field of research, born from structural optimization, that optimizes systems in environments where many subsystems and components are interacting with each other. These couplings are handled directly in MDO and used to improve optimization efficiency and effectiveness. The couplings that attach the subsystems are not just physical (i.e. air disturbance or bolt connections), but can also be such types as information (i.e. pressure and speed data). Exergy, as a subsystem and system attribute may be represented as information being passed, may be indirectly passed along through physical couplings (such as air flow), or may be passed to the system as a subsystem attribute to be used in a system objective function, such as the minimization of exergy loss. MDO provides a proven framework for exergy to be incorporated in[13], and more research is needed to understand exergies roles and presence in such frameworks.

A robust system design is one that does not radically deviate from expected behavior in response to small perturbations in operating environment or input. Exergy based analysis methods can be utilized with sensitivity analysis to identify those components of a system that are most susceptible to these extreme departures, due to the fact that exergy based analyses take all domains into account across couplings. A future area of research will be exergy's incorporation into the MDO method of Global Sensitivity Equation (GSE)[14] which uses the couplings between and within subsystems as a means to determine the impact of changes in design variables and parameters on the system as a whole. Another important research area to be examined in the future is the role of exergy in robust design methodologies. This includes such methods as Robust Design Optimization (RDO) and Reliability-Based[15] Design Optimization (RBDO). It is also important to understand exergy's role in decision theory approaches such as Utility Theory[16]. In Utility Theory exergy would be, or be part of, the measurement, and a risk preference would be applied upon the measurement. An optimization would then optimize the expected utility instead of a deterministic value, as the uncertainties would be captured directly. Through this optimization the most preferred design, using both value and risk preferences, would be determined from the set of alternatives examined.

As noted in the Section 2, exergy based analysis can provide an overall metric of system efficiency. This exergy efficiency is based on the entire integrated system, which will enable stakeholders to rank order designs based on efficiency and choose the most efficient. Exergy based efficiency function can also be used as an objective function for MDO, allowing designs and processes which maximize efficiency to be selected. MDO only provides a framework for optimization, requiring an objective function, and typically constraints, to be defined separately. The formation of objective functions, incorporating exergy, that capture the true preference of the stakeholder is an important research topic and is discussed in more detail in section 4.

A system's undesired consequences can include wasted energy in the form of heat or vibration, unintended interactions with other systems, or pollution. Because exergy and entropy are intimately related (equation 1), exergy based analysis allows for irreversible system losses to be identified. As sustainability and minimization of wasted energy become increasingly important issues for large design firms, exergy analysis provides a method of identifying the main drivers of irreversible losses of systems. Topics of sustainability are explored in Section 5. By incorporating exergy in the objective function, some forms of unintended consequences, mentioned above, can be captured directly. This again points to the need for further research in the relationship between exergy and the stakeholder's true value preference.

3.1. Exergy Based Design Analysis

A number of exergy based design tools have been developed which show exergy can aid in the search for effective designs. These methods can assess performance and efficiency of system designs, as well as aid in the preliminary design and optimization of designs. Camberos and Moorhouse have demonstrated the use of exergy for the design, analysis, and optimization of hypersonic aircraft[17]. Riggins used exergy based methods to assess

performance of Brayton cycle engine[18], as well as hypersonic aircraft[19]. Doty[20] showed that exergy based methods can aid in the integration and operation of system components. Exergy based analyses have been used to assess the performance and efficiency of a multitude of power generating plants[21], including coal[22], fossil-fuel[23], and nuclear plants[24]. These different areas of application highlight both exergy's ability to be used in diverse fields, as well as the ability to be incorporated in low level objective functions.

3.2. Rocket System Case Study

A brief overview of how exergy can benefit one particular field, the design of a rocket system, follows. An exergy balance equation for aerospace systems is shown in equation 5.

$$\Delta \boldsymbol{m_p} \left(H_p + \frac{V_e{}^2}{2} \right) - \int_{mission} T_i dS_{irr(total)} = \Delta \left(m_{veh} \frac{V_{veh}{}^2}{2} \right) + \Delta(m_{veh}gz) \quad (5)$$

The first term on the left hand side is the amount of exergy expended by the propellant. The second term on the left hand side is the sum of the exergy losses (entropy generation) across the mission trajectory. The first term on the right hand side is the change in kinetic exergy due to kinetic energy change. The final term on the right hand side is the exergy change due to the change in potential energy of the vehicle. It is clear in this equation the incorporation of not only the first law of thermodynamics, but also the second law.

Exergy is an additive attribute of a system, therefore the exergy usage and exergy destruction of one rocket stage can be summed with the exergy usage and exergy destruction of subsequent rocket stages to assess the exergy efficiency of the overall integrated system. Equation (2) can be used with these total exergy values to determine the overall efficiency of a rocket system. By assessing the efficiency of a rocket, decision makers can rank order design alternatives based on exergy efficiency and make informed decisions based on a system level attribute. Gilbert[25] and Watson[26] have shown this exergy efficiency analysis for case study rocket systems and NASA launch vehicles, leading to analyses that informed designs in ways other non-holistic attributes could not.

It will be shown in a future work by the authors that the ideal rocket equation can be obtained from equation 5 by taking the derivative of exhaust velocity. This shows that exergy based analysis contains not only the traditional performance metrics of a rocket, but also takes into account the irreversible losses experienced by a rocket. In other words, the exergy analysis accounts for past effectiveness and efficiency metrics as well as some system unintended consequences, key considerations in the design for an elegant system.

The loss term of equation 5 can be decomposed into specific irreversible losses, such as losses due to drag,
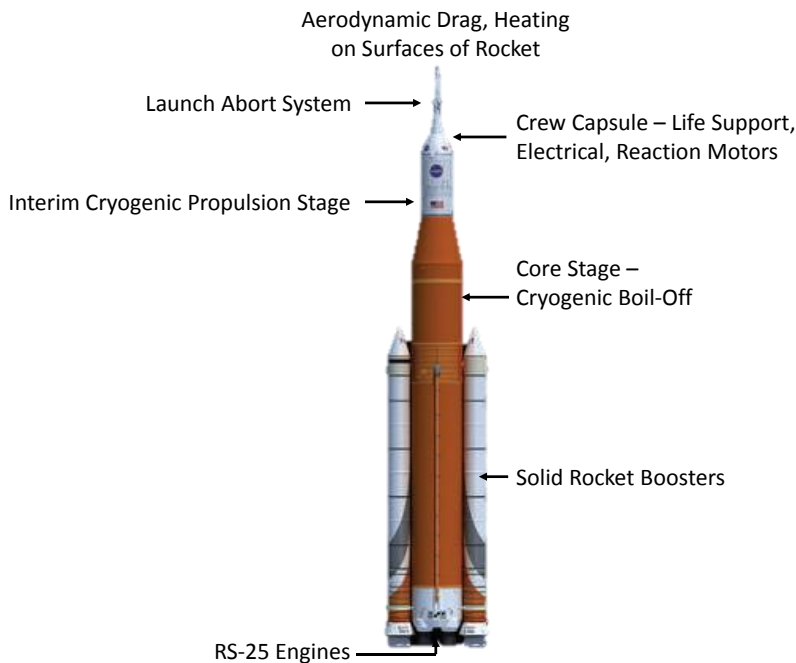

Figure 3:Potential Subsystems to Include in Exergy Analysis (image:nasa.gov)

thermal heating, and vibration loads. By decomposing the loss term into specific losses, decision makers can identify technological and process improvements and direct effort towards those parts that will yield the greatest efficiency improvements. Figure 3 shows a few example subsystems in which losses are present. Exergy analysis can identify the causes, locations, and magnitudes of these losses. The rocket experiences aerodynamic drag and aerodynamic heating losses as it travels through the atmosphere. The launch abort system contains propellants which may fire in the event of catastrophe. The crew capsule contains many subsystems which rely on energy, such as life support, electrical systems, and the reaction motors on the exterior. The core stage of the rocket contains cryogenic propellants which boil off due to the temperature of the atmosphere. Finally, the solid rocket boosters and RS-25 engines use the chemical energy stored in propellants to impart thrust forces on the vehicle, with losses in the form of heat and vibration. This future research will be important as it will provide design and system engineers a tool to focus their efforts as it relates to thermodynamic efficiencies.

Exergy analysis for a rocket system can be used as an objective function within MDO frameworks to maximize the exergy efficiency of the rocket system. Figure 4 shows a typical curve of exergy efficiency vs. vehicle velocity for an example two stage rocket.

In a submitted conference paper[27], the staging times of a rocket system are adjusted to maximize the exergy efficiency of a rocket. The curve seen in Figure 2 represents efficiency, with the highest point indicating the point at which the rocket system is most efficient. After this maxima, the efficiency trends downward, followed by a large drop due to the separation of stage dry mass. This separation is typical in large rocket systems where segments are removed as their associated fuel is burned up. This separation is performed to reduce the amount of mass that is taken to orbit, and hence reducing the amount of work required by the system. The downward trend of the curve has been seen to be caused by the loss of potential energy due to late separation of heavy rocket stages. By separating a rocket stage at the point of maximum efficiency, the final total efficiency of the payload can be increased. Optimizing the separation point, through use of data provided by exergy analysis, will enable a more efficient system. This was previously not possible to explore as the exergy of the system was not previously being calculated.

It is clear that System design and exergy have many intersections that need to be explored in future work. This future work includes: the intersection of exergy with MDO; the incorporation of exergy into objective functions in MDO frameworks; the formation of objective functions based solely on exergy and their impact on the design; the use of exergy in robust design methodologies; the use of exergy as a measurement in utility functions; and the amount of unintended consequences that are captured in exergy analyses. As exergy relates to the design of rocket systems, future work includes improving the understanding of how exergy and the traditional rocket equation are related, capturing more losses in the analyses (such as turbulence losses), developing methods or tools to help guide systems engineers in resource allocation, and in the use of exergy in optimization of rockets, particularly for stage separation determination. Future work by the authors will explore component selection for the design of a rocket, using efficiency as the objective which will be maximized.
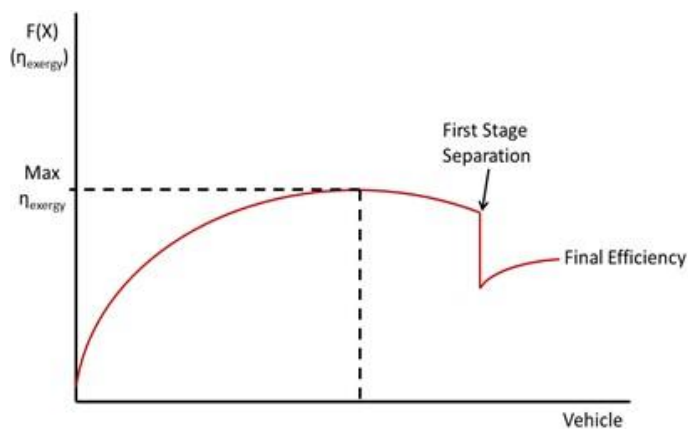

Figure 4: Efficiency Plot of a Rocket System

4. Exergy, Cost, and Value

In addition to design analysis, exergy based cost analyses provide a research area to improve systems engineering. In a field known as thermo-economics[28], or exergo-economics[29], cost functions have previously been developed using exergy. These cost functions can determine the cost of processes used to produce goods, in terms of $/J[28], [30]. By analyzing the exergetic cost, a production line can be optimized, via component or process, to minimize the overall cost per unit of goods[31]. The method of exergy cost optimization can also be extended to optimize the operation of a system, such as a power plant[30]. Incorporating exergy into cost enables the formation of an objective function that is more akin to the types of preferences seen in commercial industry. The reduction of cost is often touted as a preference, although the argument can be easily made that the true preference is profit, with cost being one of two main drivers (the other being revenue). The formation of this cost function, and its use in engineering design is an area deep in research need.

Value Driven Design (VDD) relates the attributes of a system to a single value, which can then be used to rank order design alternatives[32]. VDD is an approach that is fundamentally different that the traditional requirements-based approach. VDD strives to identify, quantify, and distribute the stakeholder's single preference, enabling design decisions that are consistent throughout the design organization. In VDD, a value function relates the system attributes to the single numerical value.[33] Because value functions are functions of attributes, and therefore also design variables, these attributes should be properly identified and carefully calculated. For example, a typical attribute of a transportation system might be the miles per gallon fuel efficiency. Because exergy based cost and exergy based efficiencies are both system level metrics, they are available as high fidelity attributes for use as system value, or for use in conjunction with other attributes to form a higher level system value. Exergy based value models will enable more informed decision making when choosing between design alternatives. Value functions incorporating exergy attributes is a future research area of the NASA Systems Engineering Consortium.

5. Exergy, Life Cycle Analysis and Sustainability

In 2009, President Obama issued an executive order[34] directing federal agencies to measure, manage, and reduce greenhouse gas emissions by developing sustainability plans. The order also directed agencies to meet energy, water, and waste reduction targets. Agencies under the order include the Department of Defense and NASA, making sustainability another systems engineering issue for which further use of exergy based analyses is beneficial.

Exergy based indices of sustainability have been developed for large scale systems. Exergy renewability indicators, which include exergy efficiencies, are used in conjunction with Life Cycle Assessment (LCA) methods to trace the "exergetic history" of a commodity from cradle to grave[35]. Exergetic Life Cycle Assessment (ELCA) extends the typical exergy analysis to include the entire life cycle of a system or process. ELCA can track the resources used by production of goods. Specifically, it quantifies the depletion of natural resources, with a distinction drawn between renewable and non-renewable resources[36], [37].

Cumulative Exergy Consumption[38] (CEC) assesses the exergy used in the production of goods. CEC tracks the resources used by processes to provide an exergy cost of J/unit. CEC assesses the exergy loss which appears in all processes of production, from the gathering of resources to the fabrication of the product itself. These exergy assessments allow for the comparison of production methods and for the imperfections of the processes to be identified. A drawback of CEC is that it does not take into account immaterial or labor factors[2].

Extended Exergy Accounting (EEA) is a standard exergy analysis, closely related to ELCA and similar to CEC, which is modified by adding equivalent exergy flows which represent capital and labor factors, which are lacked by CEC[39]. The equivalent labor flow includes both blue and white-collar activities, based on metabolic rates and work imparted by humans onto production equipment. Capital flows include the facilities and equipment required for a production line itself. EEA tracks exergy flow across the lifespan of a system or product, from construction to decommissioning and clean-up. By evaluating the exergy usage and entropy generation across the life of a system, steps can be taken towards sustainability. Optimization techniques can be utilized to minimize entropy generation and wasted exergy, such as waste heat, mechanical vibration, acoustical losses, etc.[39] Future work in the sustainability area will explore the use of exergy in design organizations, in manufacturing processes, in end of life processes, and in system level conceptual decision-making.

6.   Complex Biological Systems

Baranger [40] defines complex systems to consist of four properties:
- Complex systems contain many components which interact in a nonlinear fashion
- Components are interdependent
- Structure of the complex system spans several scales (abstraction and elaboration of a hierarchy)
- Complex systems are capable of emerging behavior (behavior is emergent if it cannot be understood by studying only the constituent behaviors of a system)

A combination of structure and emergent behavior leads to a self-organizing system. Examples of exergy as a measure of the level of organization and information content of self-organizing biological systems has been shown by Bastianoni and Marchettini[41]. Fath and Cabezas[42] compared exergy with Fisher information as indices for the ecological modelling of a food web; exergy was shown to be suited for ecological applications due to the fact it measures energy and biomass. Research in exergy's applicability to biologically complex systems may provide insight into poor assumptions or missed concepts that would otherwise not be realized.

7.   Exergy and Information Theory

In the field of Information Theory, Shannon introduced an entropy function which describes the state of a system of incomplete information based on the number of bits of information required to define that state[43]. Because this state of information can be described by entropy, this implies that a state of information can be defined by exergy[2]. This also implies that exergy can be a measure of system information. Brillouin reached a similar conclusion, stating that "information gain means an increase in entropy...[44]." Jaynes[45] showed that statistical mechanics is an instance of information theory, by deriving Gibbs' entropy results from Shannon's entropy. Wall[46] extended the work of Jaynes by using Boltzmann entropy to relate information entropy to exergy, resulting in an amount of exergy connected to a bit of information. Lindgren[47] explored a similar relationship between exergy and information, by producing a thought experiment in which two gases are mixed. The mixed gases result in a relation between exergy per molecule and information loss.

However, there is still disagreement on the matter of relating classical thermodynamical entropy to Shannon's entropy. Kline[48], [49] argued that the dimensional equivalence between thermodynamic entropy and Shannon entropy are not equivalent. If the two types of entropy are not dimensionally equivalent, then exergy must also not be. Sciubba agrees, stating that "the few attempts to define 'the exergy content of one bit of information'... strongly suffer from a lack of well-founded theoretical development.[2]" Another method, also under debate, of relating exergy to information content is to analyze the physical resources and exergy needed to produce and send a bit of information, by using CEC or EEA[2].

The debate makes it clear that any possible links between information theory and exergy are fertile ground for research. A link between exergy and information theory could provide a means of improving communications, computing and data compression.

8.   Exergy and Other Disciplines

8.1. Controls

Exergy has also been used as a basis for control methods. Most traditional control design is based on approximating nonlinear systems as linear systems, resulting in performance losses. Robinett and Wilson used exergy generation and exergy dissipation terms to evaluate control system performances, resulting in a nonlinear control method. The exergy based control method was demonstrated on a two degree of freedom robot, resulting in stability of the system[50]. Robinett and Wilson expanded the use of exergy based controls into a distributed decentralized control law for collective robotic systems. In addition to using information theory, exergy and entropy concepts were once again used to develop control laws for collective and individual robots. This method was demonstrated via numerical simulation[51].

Nonlinear control systems which are based on exergy have been shown to result in improved performance over linear based control methods. Higher performing control systems will result in higher performing and more efficient systems. Research into exergy's place in control methods will benefit the search for elegant design.

8.2. Electrical Systems

In addition to the power generating plants, mentioned in Section 3.1, other systems which use electricity can be analyzed by exergy based methods. Rosen has demonstrated the use of exergy based concepts when studying the efficiencies of systems which use and convert electrical energy. Systems explored include electromagnetic coils and mechanical armatures, in which the mechanical work done by a magnetic field is assessed[52]. In another work by Rosen and Bulucea, other electrical systems are considered, including electrical conversion devices, electrical storage systems, and systems driven by electricity. The efficiencies of these devices are determined, which allows for possible improvements to be identified[53].

It is demonstrated in these examples that exergy once again provides a means of evaluating efficiencies of these systems. Further research into the use of exergy analysis on electrical systems will yield performance and sustainability benefits related to the increasing the efficiencies of these systems.

8.3. Heat Transfer

Bejan[54] authored a review paper devoted to assessing the thermodynamic irreversibilities of heat and mass transfer systems. Methods of entropy minimization by exergy analysis are investigated, along with design tradeoffs between heat transfer and fluid flow irreversibilities. Devices analyzed include heat exchangers, thermal energy storage devices, and mass exchangers. The exergy of thermal radiation has been explored by Patela[55]. Formulas for the computation of exergy of radiation are presented. Heat transfer is of great interest for exergy based analyses, especially in the realm of sustainability, where heat waste accounts for large portions, roughly thirty percent[56], of energy loss in industrial processes.

Aerodynamic heating is a concern for hypersonic aircraft and aerospace vehicles. Exergy analysis can identify the losses associated with heating due to highspeed airflow[13]. The identification of these losses allow for improvements and optimization of aircraft design.

8.4. Space Habitats and Life Support

As briefly mentioned in Section 1.2, manned space vehicles and habitats require life support systems to keep the crew alive. These systems consist of ventilation, carbon dioxide scrubbing, and environmental controls, each with their respective energy losses. The authors are currently investigating the use of exergy analysis on the International Space Station's life support system. Life support systems are a crucial component of manned space systems, so benefits gained by exergy based methods are benefits passed up to the overall system, thereby improving the efficiency and performance.

9. Conclusion

Exergy is the useful work available to a system. It is an overall system metric which encompasses the interactions between subsystems and across disciplines. Multiple examples, including a rocket design example discussed in this paper, have shown that exergy is a useful attribute to consider in systems engineering design. Exergy based analysis, including exergy efficiency analysis, provides advantages over traditional engineering analyses due to the underlying incorporation of the second law of thermodynamics. As an analysis approach the benefits of exergy and the work needed to improve acceptance by the engineering community are clear.

The true need from engineering is at the systems engineering level in how to handle the design of the ever more complex systems that are being created. It is clear that the current approach to systems engineering needs modification or replacement in order to reliably produce elegant systems. Mathematically founded approaches to design, such as MDO, VDD, and decision analysis have been proposed, as well as a mix of these. Exergy, as a holistic system attribute that can be decomposed into subsystem attributes, is a prime candidate to be captured, directly or indirectly (depending on preference), in the objective/value/measurement function that these approaches require. Such a holistic value function would enable systems to be rank ordered and for stakeholders and engineers throughout the organization to make informed decisions when faced with different design alternatives.

Exergy is also shown to be useful in LCA when faced with the growing concerns of sustainable processes. Exergy based cost modelling approaches can be used to reduce the cost of production of goods, or generation of power. Finally, it is shown that exergy can even be extended into the domain of self-organizing biological systems.

These areas all represent vast research areas that can be examined to build up the use of exergy in systems engineering and design.

10. Acknowledgements

11. References

[1] J. Szargut, *Exergy Method: Technical and Ecological Applications*. WIT Press, 2005.

[2] E. Sciubba and G. Wall, "A brief commented history of exergy from the beginnings to 2004," *Int. J. Thermodyn.*, vol. 10, no. 1, pp. 1–26, 2007.

[3] Y. A. Cengel, *Introduction to Thermodynamics and Heat Transfer*. McGraw-Hill Higher Education, 2008.

[4] I. Maddox, P. Collopy, and P. A. Farrington, "Value-Based Assessment of DoD Acquisitions Programs," *Procedia Comput. Sci.*, vol. 16, pp. 1161–1169, 2013.

[5] D. J. Moorhouse, "Introduction: Exergy," *J. Aircr.*, vol. 40, no. 1, pp. 10–10, 2003.

[6] M. D. Griffin, "How do we fix System Engineering?," in *61st Annual International Congress, Prague, Czech Republic*, 2010, vol. 27.

[7] C. L. BLOEBAUM, P. HAJELA, and J. SOBIESZCZANSKI-SOBIESKI, "Non-Hierarchic System Decomposition in Structural Optimization," *Eng. Optim.*, vol. 19, no. 3, pp. 171–186, May 1992.

[8] J. Sobieszczanski-Sobieski and R. T. Haftka, "Multidisciplinary aerospace design optimization: survey of recent developments," *Struct. Optim.*, vol. 14, no. 1, pp. 1–23, Aug. 1997.

[9] J. SOBIESZCZANSKI-SOBIESKI, B. B. JAMES, and A. R. DOVI, "Structural optimization by multilevel decomposition," *AIAA J.*, vol. 23, no. 11, pp. 1775–1782, 1985.

[10] P. HAJELA, C. L. BLOEBAUM, and J. SOBIESZCZANSKI-SOBIESKI, "Application of global sensitivity equations in multidisciplinary aircraft synthesis," *J. Aircr.*, vol. 27, no. 12, pp. 1002–1010, 1990.

[11] K. Lewis and F. Mistree, "Collaborative, Sequential, and Isolated Decisions in Design," *J. Mech. Des.*, vol. 120, no. 4, pp. 643–652, Dec. 1998.

[12] J. R. R. A. Martins and A. B. Lambe, "Multidisciplinary Design Optimization: A Survey of Architectures," *AIAA J.*, vol. 51, no. 9, pp. 2049–2075, 2013.

[13] J. A. Camberos and D. J. Moorhouse, *Exergy Analysis and Design Optimization for Aerospace Vehicles and Systems*, vol. 238. Reston, VA: American Institute of Aeronautics and Astronautics, 2011.

[14] J. SOBIESZCZANSKI-SOBIESKI, "Sensitivity of complex, internally coupled systems," *AIAA J.*, vol. 28, no. 1, pp. 153–160, 1990.

[15] J. Tu, K. K. Choi, and Y. H. Park, "A New Study on Reliability-Based Design Optimization," *J. Mech. Des.*, vol. 121, no. 4, pp. 557–567, 1999.

[16] J. V. Neumann and O. Morgenstern, *Theory of Games and Economic Behavior*. Princeton University Press, 1947.

[17] J. A. Camberos and D. J. Moorhouse, "Systems Engineering in Terms of Exergy," *Int. J. Aerosp. Eng.*, vol. 2009, pp. 1–7, 2009.

[18] D. W. Riggins, "Brayton cycle engine/component performance assessment using energy and thrust-based methods," *AIAA Pap.*, vol. 96, p. 2922, 1996.

[19] D. W. Riggins, T. Taylor, and D. J. Moorhouse, "Methodology for Performance Analysis of Aerospace Vehicles Using the Laws of Thermodynamics," *J. Aircr.*, vol. 43, no. 4, pp. 953–963, 2006.

[20] J. H. Doty and J. A. Camberos, "Statistical, Modular Systems Integration Using Combined Energy & Exergy Concepts," in *48th AIAA Aerospace Sciences Meeting*, 2010, pp. 04–07.

[21] M. A. Habib and S. M. Zubair, "Second-law-based thermodynamic analysis of regenerative-reheat Rankine-cycle power plants," *Energy*, vol. 17, no. 3, pp. 295–301, Mar. 1992.

[22] M. A. Rosen, "Energy- and exergy-based comparison of coal-fired and nuclear steam power plants," *Exergy Int. J.*, vol. 1, no. 3, pp. 180–192, 2000.

[23] J. H. Horlock, J. B. Young, and G. Manfrida, "Exergy Analysis of Modern Fossil-Fuel Power Plants," *J. Eng. Gas Turbines Power*, vol. 122, no. 1, pp. 1–7, Jul. 1999.

[24] M. A. Rosen and D. S. Scott, "Energy and exergy analyses of a nuclear steam power plant," 1986.

[25] A. Gilbert, B. Mesmer, and M. D. Watson, "Exergy analysis of rocket systems," in *Systems Conference (SysCon), 2015 9th Annual IEEE International*, 2015, pp. 283–288.

[26] M. D. Watson, A. Gilbert, and B. Mesmer, "Launch Vehicle Exergy Analysis," in *Proceedings of the 43rd Structures and Mechanical Behavior*, Salt Lake City, 2015.

[27] A. Gilbert, B. Mesmer, and M. D. Watson, "Exergy Based Optimization of Rocket Staging Times," in *Systems Conference (SysCon), 2016 10th Annual IEEE International*, 2016.

[28] M. A. Lozano and A. Valero, "Theory of Exergetic Cost and Thermoeconomic Optimization," *Energy*, vol. 18, no. 9, pp. 939–960, Sep. 1993.

[29] G. Tsatsaronis, L. Lin, and J. Pisa, "Exergy Costing in Exergoeconomics," *J. Energy Resour. Technol.*, vol. 115, no. 1, pp. 9–16, Mar. 1993.

[30] H.-Y. Kwak, D.-J. Kim, and J.-S. Jeon, "Exergetic and thermoeconomic analyses of power plants," *Energy*, vol. 28, no. 4, pp. 343–360, Mar. 2003.

[31] G. Tsatsaronis and M. J. Moran, "Exergy-aided cost minimization," *Energy Convers. Manag.*, vol. 38, no. 15–17, pp. 1535–1542, Oct. 1997.

[32] G. Richardson, J. Penn, and P. Collopy, "Value-centric analysis and value-centric design," in *AIAA SPACE Conference and Exposition*, 2010.

[33] P. D. Collopy and P. M. Hollingsworth, "Value-driven design," *J. Aircr.*, vol. 48, no. 3, pp. 749–759, 2011.

[34] "Executive Order 13514 -- Focused on Federal Leadership in Environmental, Energy, and Economic Performance," *whitehouse.gov*. [Online]. Available: https://www.whitehouse.gov/the-press-office/president-obama-signs-executive-order-focused-federal-leadership-environmental-ener. [Accessed: 02-Dec-2015].

[35] A. Zvolinschi, S. Kjelstrup, O. Bolland, and H. J. Kooi, "Exergy Sustainability Indicators as a Tool in Industrial Ecology," *J. Ind. Ecol.*, vol. 11, no. 4, pp. 85–98, Feb. 2008.

[36] R. L. Cornelissen and G. G. Hirs, "The value of the exergetic life cycle assessment besides the LCA," *Energy Convers. Manag.*, vol. 43, no. 9, pp. 1417–1424, 2002.

[37] R. U. Ayres, L. W. Ayres, and K. Martinás, "Exergy, waste accounting, and life-cycle analysis," *Energy*, vol. 23, no. 5, pp. 355–363, 1998.

[38] J. Szargut, "Analysis of cumulative exergy consumption," *Int. J. Energy Res.*, vol. 11, no. 4, pp. 541–547, Oct. 1987.

[39] E. Sciubba, "Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems," *Exergy Int. J.*, vol. 1, no. 2, pp. 68–84, Jan. 2001.

[40] M. Baranger, "Chaos, complexity, and entropy," *N. Engl. Complex Syst. Inst. Camb.*, 2000.

[41] S. Bastianoni and N. Marchettini, "Emergy/exergy ratio as a measure of the level of organization of systems," *Ecol. Model.*, vol. 99, no. 1, pp. 33–40, Jun. 1997.

[42] B. D. Fath and H. Cabezas, "Exergy and Fisher Information as ecological indices," *Ecol. Model.*, vol. 174, no. 1–2, pp. 25–35, May 2004.

[43] C. E. Shannon, "A Mathematical Theory of Communication," *SIGMOBILE Mob Comput Commun Rev*, vol. 5, no. 1, pp. 3–55, Jan. 2001.

[44] L. BRILLOUIN, "THERMODYNAMICS AND INFORMATION THEORY," *Am. Sci.*, vol. 38, no. 4, pp. 594–599, 1950.

[45] E. T. Jaynes, "Information Theory and Statistical Mechanics," *Phys. Rev.*, vol. 106, no. 4, pp. 620–630, May 1957.

[46] G. Wall, *Exergy: a useful concept*. Göteborg: TH, 1986.

[47] K. Lindgren, "Information theory for complex systems," *Lect. Notes Dep. Phys. Resour. Theory Chalmers Göteb. Univ. See Httpfrt Fy Chalmers Secscascoursesinfotheorylecturenotes Html*, 2003.

[48] P. A. Corning and S. J. Kline, "Thermodynamics, information and life revisited, Part I: 'To be or entropy,'" *Syst. Res. Behav. Sci.*, vol. 15, no. 4, pp. 273–295, Jul. 1998.

[49] P. A. Corning and S. J. Kline, "Thermodynamics, information and life revisited, Part II: 'Thermoeconomics' and 'Control information,'" *Syst. Res. Behav. Sci.*, vol. 15, no. 6, pp. 453–482, Nov. 1998.

[50] I. Rush D. Robinett and D. G. Wilson, "Exergy and Entropy Thermodynamic Concepts for Nonlinear Control Design," pp. 119–128, Jan. 2006.

[51] I. Rush D. Robinett and D. G. Wilson, "Decentralized Exergy/Entropy Thermodynamic Control for Collective Robotic Systems," pp. 1447–1453, Jan. 2007.

[52] WSEAS International Conference, P. Dondon, and WSEAS (Organization), Eds., *Recent advances in engineering education*. [Stevens Point, Wis.]: WSEAS Press, 2009.

[53] M. A. Rosen and C. A. Bulucea, "Using Exergy to Understand and Improve the Efficiency of Electrical

Power Technologies," *Entropy*, vol. 11, no. 4, pp. 820–835, Nov. 2009.

[54] A. Bejan, "The thermodynamic design of heat and mass transfer processes and devices," *Int. J. Heat Fluid Flow*, vol. 8, no. 4, pp. 258–276, Dec. 1987.

[55] R. Petela, "Exergy of Heat Radiation," *J. Heat Transf.*, vol. 86, no. 2, pp. 187–192, May 1964.

[56] "Waste Heat to Power Systems," Environmental Protection Agency, 2012.